SLIPPING ZONE LOCATION IN SQUEEZE FLOW

PATRICE ESTELLÉ (✉)

LGCGM, Département Matériaux et Thermique de l'Habitat, Institut National des Sciences Appliquées, 20 avenue des Buttes de Coësmes, CS 14315, 35043 Rennes, France

Email : *patrice.estelle@insa-rennes.fr*
Tel : +33 (0) 2 23 23 82 00
Fax : +33 (0) 2 23 23 84 48

CHRISTOPHE LANOS

LGCGM, Département Matériaux et Thermique de l'Habitat, Institut Universitaire Technologique, rue du Clos Courtel, BP 90422, 35704 Rennes Cedex 7, France

Email : Christophe.Lanos@univ-rennes1.fr
Tel : +33 (0) 2 23 23 67 40

ARNAUD PERROT

LGCGM, Département Matériaux et Thermique de l'Habitat, Institut National des Sciences Appliquées, 20 avenue des Buttes de Coësmes, CS 14315, 35043 Rennes, France

Email : arnaud.perrot@ens.insa-rennes.fr
Tel : +33 (0) 2 23 23 82 00

COLIN SERVAIS

Nestlé Research Center, Vers-chez-les-Blanc, CH-1000 Lausanne 26, Switzerland

Email : colin.servais@rdls.nestle.com

Abstract

In squeeze flow rheometry, the main problem is the boundary condition between the squeezed material and the plates. So, the crucial assumption is to know the location and the shape of the sample part where wall slip may or may not occurs. This question is investigated from experimental results. For this, squeeze flow experiments are carried out to visualize the flow pattern at the walls. Influence of boundary conditions is particularly studied using different plate surface condition. As a result, with wall slipping conditions, we propose a flow modelling divided into two zones. A circular central zone of the sample sticks on the plates ; beyond that zone the sample slips at the plates with friction.

Keywords

Squeezing, Wall Slip, Flow visualization, Flow Modeling

Introduction

Squeeze flow rheometry is used increasingly as a means for measuring the shear and biaxial elongational viscosity (Chatraei et al. 1981; Kompani and Venerus 2000; Nasseri et al. 2004), the liquid-solid relative motion of pastes (Sherwood 2002; Roussel et al. 2003), and particularly the rheological properties of many fluids (Meeten, 2004). A fluid sample is squeezed between two rigid circular parallel plates by either applying a constant force to the upper plate or by moving it at constant compression speed, with the lower plate remains stationary. A number of different exact or approximated solutions of such a flow have been established. These solutions depend on fluid rheological behavior, boundary and outer edge conditions at the plates. Recently, a review of squeeze flow solutions with slipping and sticking conditions is given by Meeten (2004). The author mentioned in particular the need to know the material-plate boundary condition to correctly interpret the material rheology. Also, rough plates are commonly used to impose sticking flow (Adams et al. 1994). Perfect slip is obtained with lubricated plates which may generate different flow regimes (Burbidge and Servais 2004). However, some slip with friction can produce during squeezing flow rather than perfect slip or stick and plays a significant role in flow development. This phenomenon depends on the solid-fluid interaction and the fluid particle size. In polymer melts, the velocity of the fluid in contact with the boundary is finite and perfect slip is assumed. For concentrated suspensions or gels, slip is only apparent. This last case corresponds to what is called wall slip depletion effects in flow (Barnes 1995). These effects are due to the displacement of the disperse phase away from solid boundaries. This gives a depleted layer of liquid which acts as a lubricant. To study this problem, the crucial assumption is to know the location and the shape of the part where wall slip may or may not occurs (Fortin et al. 1991). Here, from experimental evidence, we propose a flow pattern to modelize the problem stated above. Such a flow pattern is divided into two zones: a circular central zone of the sample sticks on the plates, beyond that zone the sample slips at the plates with friction.

Background

Users of squeeze flow often assume boundary slip, or no-slip, but few contributions give solution with partial slip or friction condition at the plates. Meeten (2000, 2001) compared the yield stress of several materials measured by squeeze flow between smooth glass plates, and by no-slip vane method. Discrepancies between the two methods suggested some slip in squeeze flow but prefect slip was not found. Laun et al. (1999) modelled slip in constant-radius geometry for purely viscous materials. In this paper, the authors proposed to evaluate the slip velocity at the radial boundary r = R from squeeze flow experiments. They reported in particular a method to make a separation between the bulk shear and the wall slip from a single test. Sherwood and Durban (1996) considered shear stress at the wall as a fixed fraction of the yield stress in shear. This led to a constant shear stress at the walls. From plastic theory, the authors found squeezing solutions of Bingham, power-law and Herschel-Bulkley fluids. An alternative was given by Adams et al. (1997). They considered a Coulombic boundary condition where the wall shear stress is related to the normal pressure. According to Adams et al. (1994), an extension of the Herschel-Bulkley equation provides a very general form of boundary conditions. Finally, in order to integrate this boundary condition, the authors modified the outer edge condition used in lubrication theory and imposed a non-zero normal pressure at the edge of the plates. Navier wall slip condition was considered by Lawal and Kalyon (2000) to compute squeeze flow of viscoplastic fluids subject to wall slip. Comparison with previous lubrication approximation results (Lawal and Kalyon 1998) shows good agreement between both methods for h/R << 0.05. Beyond, the Navier assumption fails, and a boundary condition as used by Adams et al. (1994) seems to be more appropriated. The works presented above deal with the form of the boundary condition at the walls. However, none of them mentioned the shape and the location of the slipping zone because it is widely assumed that slip occurs on the full plate surface. This question is investigated in the next section from experimental results. For this, squeeze flow experiments are carried out to visualize the flow pattern at the walls. Influence of boundary conditions is particularly studied using different plate surface condition.

Experimental evidence: flow visualization and surface plate influence

The fluid used for these experiments is modelling clay Plasticine. Such a fluid has been shown to be elastic over an initial squeeze amplitude of about 5% of the sample height, becoming mainly plastic thereafter (Adams et al. 1997). The yield stress of Plasticine is measured with vane geometry in rate controlled mode as the maximum shear stress value

(Barnes and Nguyen 2001). In this way, tests are carried out at a constant and low rotational rates (0.1, 0.5 and 1 rpm). Vane tests are performed on a Brookfield Soft Solid Tester and the four-bladed probe used is 8 mm in diameter and height. As a result, the Plasticine exhibits a yield stress of 25 kPa which does not depend on the rotational rate considered.

Squeeze flow experiments are carried out in starting constant volume geometry and at ambient temperature. Squeeze tests are carried out using an hydraulic press on cylindrical samples with reduced slenderness. The apparatus consists in two coaxial circular and parallel plates without any rotation. The lower disc is displaced at controlled constant velocity (0.3 $mm.s^{-1}$), while the upper one is maintained stationary. Since the compression machine used here is designed to study rather solid materials, the maximum force value is 20 kN and the uncertainty is +/- 0.01 kN. The gap between the plates is measured using a lvdt strain gauge with 150 mm maximum stroke and +/- 0.1 mm accuracy. The Plasticine samples used are 50 mm in diameter and about 17 mm in height. The samples are placed between a Plexiglass® plate assembly of 120 mm in diameter. Several concentric circular coloured lines are made on the surface samples. They are used to detect the occurrence of slip at the plate surface. The marker used for the rings is coloured fine inorganic powder. The thickness of the coloured rings is sufficiently low (1 mm) to avoid its influence on the plate flow condition.

A camera is used to show pictures of the flow at the wall for several consecutive compression height: at initial height of the sample, then approximately at 75, 50 and 25% of this height (figure 1). It is important to note that the enlargement of the images is different from one pictures to the next in order to correctly show the flow behaviour of the plasticine at the plates during the squeezing. Stick of the Plasticine on the plates is induced by leaving dry clay powder between the sample and the solid surfaces. The dry clay powder behaves as a Coulomb material. To ensure a plastic flow in the thin layer of powder, the normal stress at the plates due to the squeezing action imposes a large shear stress in the thin layer. The shear stress required in the powder layer is higher than the yield shear stress of plasticine. Also, the powder acts as a rough thin layer which is sufficient to ensure no-slip at the plates.

For tests with partial slip, no treatment is applied on the plate surfaces. The results of the visualization experiments are presented in Fig. 1. Fig. 1(a) shows the flow surface for Plasticine in slipping condition and Fig. 1(b) shows the one in sticking condition.

As shown Fig. 1(a), we note an homothetic growth of the circular coloured lines which can be explained by slipping conditions. This result is coherent with the quite extensional flow field of mainly plastic fluid like Plasticine (Adams et al. 1997). However, a circular central zone does not undergo such an expansion. This central zone keeps no-slip boundary conditions for high squeeze pressure. The evolution of the coloured ring thickness is low which expresses a relative no-slip boundary condition. The boundary between both flowing zones evolves with the decrease of the compression height.

As shown Fig. 1(b), the evolution of the circular coloured lines proves true the no-slip boundary condition between the sample of Plasticine and the plates. Actually, the circular lines rapidly get out of shape and thickness during the squeezing. At the end of the test, these circular lines cannot be identified any longer. Moreover, for no-slip boundary condition, Fig. 1(b) shows that the shape of the central ring is unchanged. So the flow presents an unyielded zone which is located near the plates and around the radial axis of symmetry. This experimental result is in agreement with numerical predictions of Smyrnaios and Tsamopoulos (2001). It can be noted that the symmetry gets lost in the last picture of figure 1b (for no-slip boundary condition) in some directions. This can be explained by the out-coming part fracture of the sample in these directions. Such fractures and defects induce energy dissipation in the flowing sample which compromises the axial symmetry of the flow. Finally, these results show that slip concern only a part of the plate surface. This part is located beyond a central zone of the sample where sticking conditions or quasi-static state of the sample appear. The material flows outward as an expanding cylindrical plug with slip at the plates beyond a slip radius, which constitutes a transition boundary.

Figure 1

Concluding remarks

The flow visualization experiments described above allow us to modelize the geometry of the slipping squeeze flow as follow (see Fig.2). A sticking zone is located in the center of the sample. Around this zone the sample slips at the plates. The boundary between these two zones is defined as a slip radius, denoted R_s, as shown figure 2. This transition point from an adhesive to a slip condition with friction is similar to the one of the numerical works of Fortin et al. (1991) and Jay and co-workers (1998) in the case of channel flows. However, in our case, the transition point moves during the test. At the beginning of the test $R_s = R$, and R_s is close to zero at the end of the test.

Figure 2

The flow pattern proposed here is an important step to predict the squeeze force of a fluid in slipping flow and correctly estimate its rheological properties. This can be done assuming the behaviour law of the fluid and determining the velocity field. Such a velocity field has to include the extensional flow component near the plate surface due to the presence of slip (Meeten, 2004) which clearly appears here in a located zone, as shown in the previous section. The velocity field has also to satisfy the equation of motions and the following boundary conditions:

1. The imposed axial velocity at the plates.
2. The continuity condition on axial and radial velocities and their derivatives must be fulfilled between the two zones, in $r = R_s$.
3. The shear stress boundary condition identified or imposed at the plates in the slipping zone.

This step is necessary to identify the slip radius position and the evolution of the friction law in the slipping zone during the test, as well as the squeeze force induced by such a flow geometry. This provides a useful potential for the simultaneous determination of rheological and tribological properties of a fluid from a single squeeze test rather than the combination of capillary and squeeze flow rheometers, as proposed by Tang and Kalyon (2004). The whole of this theoretical analysis is the goal of a forthcoming paper.

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Figure Caption

Figure 1. Visualisation of plate surface plasticine flow ; (a): partial slip flow, (b): sticking flow.

Figure 2. Partial slip squeeze flow modeling.

Figure 1. Visualisation of plate surface plasticine flow ; (a): partial slip flow, (b): sticking flow.

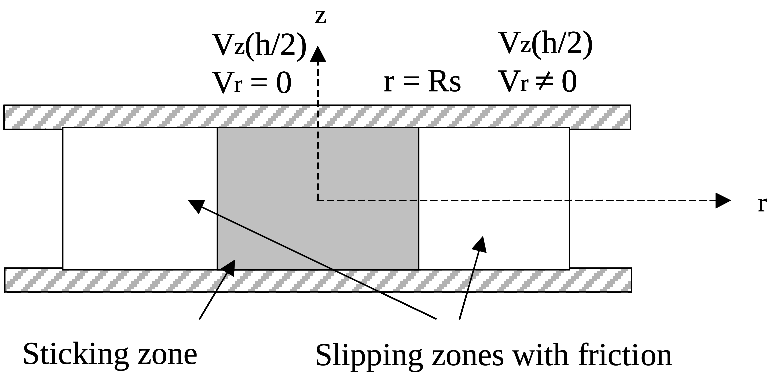

Figure 2. Partial slip squeeze flow modeling.